



Executive Summary

As NASA plans to return to the moon during the Artemis missions, important lessons can be drawn from the Apollo missions of the '60s and '70s. The Apollo Lunar Module (LM) successfully supported lunar descent, landing, EVA operations, all necessary crew functions for the duration of the mission and ascent from the surface. Using it as a starting point for reference can save time and resources for new designs, as well as provide the opportunity to address past issues.

Relevant Standards

NASA-STD-3001 Volume 1, Rev B

[V1 3000] Medical Management
[V1 3003] In-Mission Preventive Health Care
[V1 3004] In-Mission Medical Care
[V1 3005] Medical Training for in-Mission Medical Care Providers
[V1 3006] Crew Medical Officers Quantity
[V1 3007] Medical Evacuation
[V1 3008] In-Mission Evacuation to Definitive Medical Care Facilities
[V1 3009] Palliative Comfort Care
[V1 3010] Termination of Care
[V1 3011] Capability to Handle Deceased Crewmembers
[V1 6007] Medical and Survival Kits

NASA-STD-3001 Volume 2, Rev C

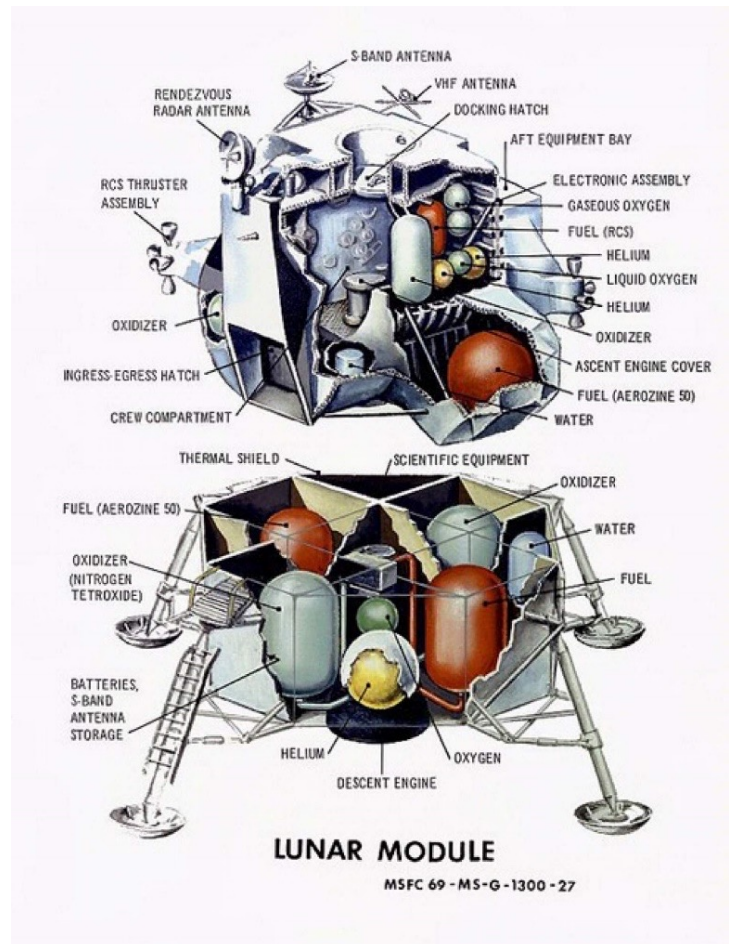
[V2 6002] Inert Diluent Gas
[V2 6003] O₂ Partial Pressure Range for Crew Exposure
[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels
[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure
[V2 6007] Rate of Pressure Change
[V2 6150] Barotrauma Prevention
[V2 6008] Decompression Sickness (DCS) Risk Identification
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[V2 6064] Sustained Translational Acceleration Limits
[V2 6065] Rotational Velocity
[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation
[V2 6067] Transient Rotational Acceleration

[V2 6069] Acceleration Injury Prevention
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[V2 7016] Personal Hygiene Capability
[V2 7020] Body Waste Management Capability
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[V2 7050] Stowage Provisions
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[V2 7064] Trash Accommodation
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[V2 8005] Functional Arrangement
[V2 8006] Interference
[V2 8007] Spatial and Interface Orientation
[V2 8013] Intravehicular Translation Paths
[V2 8027] Hatchway Size and Shape
[V2 11005] EVA Translation Path Hazard Avoidance
[V2 8033] Restraints for Crew Tasks
[V2 8038] Restraint and Mobility Aid Standardization
[V2 8040] Mobility Aid for Assisted Ingress and Egress
[V2 8041] Unassisted Ingress, Egress, and Escape Mobility Aids
[V2 8042] Mobility Aid Provision
[V2 10030] Display and Control Location and Design
[V2 11001] Suited Donning and Doffing

Background

Lunar Module Details

- Mass (fully loaded): 16,375 kilograms (kg)
- Mass of crew and supplies:
 - Crew: 2x75 kg
 - Suits: 2x82 kg
 - Food: 0.77 kg per man per day
 - Water: 580 kg (Apollo 11)
- Pressurized volume: 6.65 cubic meters (cu. m)
- Habitable volume: 4.53 cu. m
- Atmosphere: 100% O₂ at 4.8 pounds per square inch (psi)
- Carbon Dioxide: 7.6 millimeters mercury (mmHg)
- Crew Size: 2 crewmembers

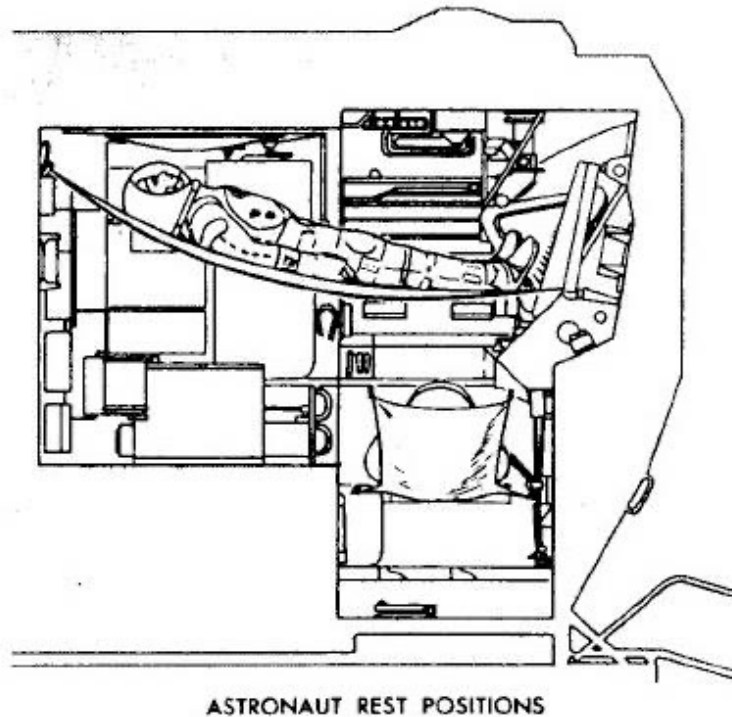


Over the course of the Apollo program, the original LM supported the Apollo 11, 12, and 14 lunar missions, allowing crew to stay on the surface of the Moon for 21-33 hours in total, with 1-2 surface EVAs totaling 2-9 hours. The LM served as an improvised “lifeboat” during the abortive Apollo 13, sustaining 3 crew for 4 days with some modifications (three times the man-days intended for the LM).

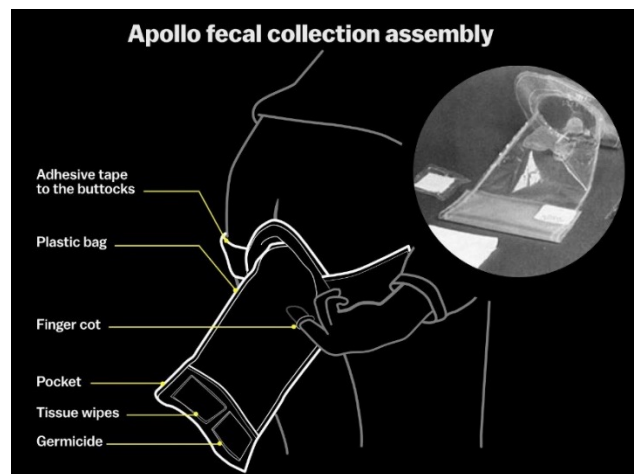
After Apollo 14, the LM underwent slight design changes. The Extended Lunar Module (ELM) was modified with more powerful descent thrust and an additional waste storage tank. It allowed for longer lunar stays during the Apollo 15, 16, and 17 missions (67-75 hours on the lunar surface, with 3-4 surface EVAs totaling 14-22 hours).

Features & Accommodations

- **Sleep:** The crew slung hammocks perpendicularly to sleep (shown right) and stowed them during normal activities.
- **Body Waste:** The Apollo LM had no installed toilet or designated toilet area. The crew used urine and fecal collection bags (shown below). To reduce mass and risk of contamination, all body waste was left on the surface of the moon before ascent.
- **Water:** Most water was stored in a tank in the descent stage for use on the moon. Some water was stored in the ascent stage for use during the ascent phase. Both tanks were accessed via the same water gun nozzle. Hot water was not available during lunar stays.
- **Food:** Food was freeze-dried, vacuum sealed, and stored in the cabin. Astronauts pumped water into the food packs and palpated them to rehydrate the food before consumption.



Urine collection device



Fecal collection assembly

Features & Accommodations

- **Navigation/Windows:** While controlling the LM's ascent and descent, the crew stood at the console, which granted them excellent visibility out the windows. This allowed the windows to be smaller, which reduced overall mass and complexity of the LM
- **Crew Restraint System:** During lunar ascent/descent and docking/undocking with the command module (CM), the crew of the LM were strapped in the restraint assembly (shown below). It applied a constant 30 pounds of downward force to stabilize the crew and keep them at the controls. Adjustable Armrests and handgrips were also utilized to maintain posture during descent and ascent.

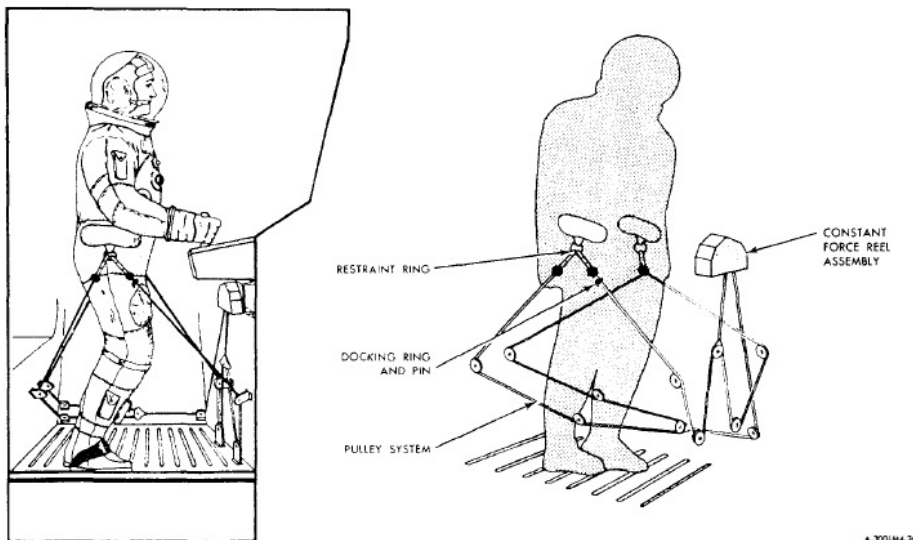


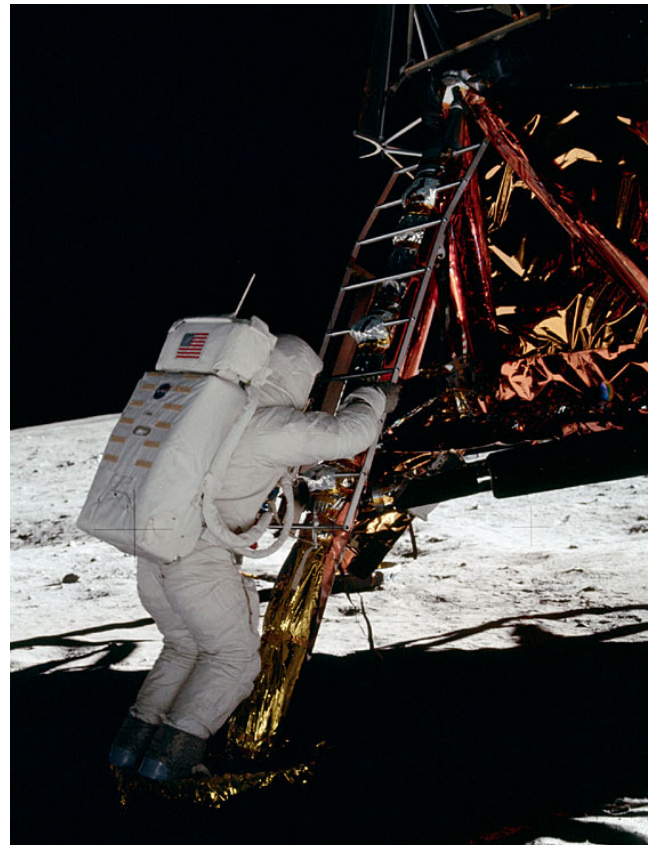
Figure 2.11-10. Restraint Equipment

- **Depressurization Operations:** The LM didn't feature an airlock, so the entire cabin was depressurized prior to lunar EVAs. As such, every piece of equipment had to withstand being in a vacuum. Food packs were vacuum-sealed, and were able to survive depressurization operations. Medication packaging also had to accommodate the lower pressure and decompression.

Design Considerations: If the crew is standing during ascent/descent, orthostatic intolerance (fainting due to transition from μg to descent acceleration profile) needs to be considered. Packaging, including food and medications, need to consider expected pressure changes.

Features & Accommodations

- Ladder:** The LM ladder (shown right) had a 9-inch spacing between rungs. This may have been too narrow; footage from the Apollo missions shows astronauts occasionally missing a rung when climbing the ladder. The bottom of the ladder was 30 inches from the footpad to account for the collapsible landing gear and unknown depth/softness of the lunar surface. The large gap added an additional challenge for astronauts climbing in and out of the LM.
- Radiation Countermeasures:** The Apollo missions occurred during periods of high solar activity, which increased exposure to solar particle events (SPEs) but reduced exposure to galactic cosmic rays (GCRs). The LM and EVA suits provided negligible shielding against GCRs; astronauts were equipped with a variety of personal and handheld radiation meters for the duration of the missions (shown below).



Exterior of the LM, showing the ladder

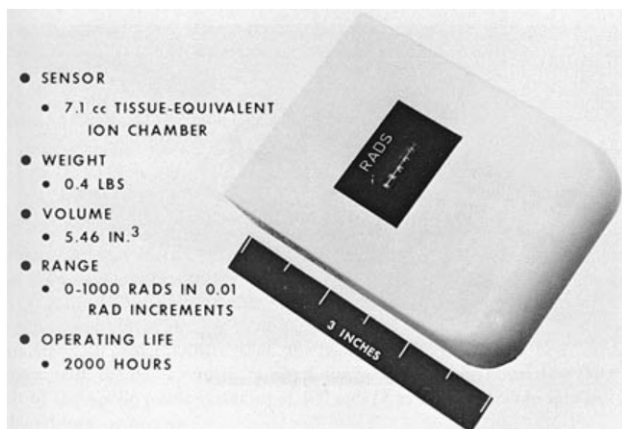


Figure 4. Personal radiation dosimeter.

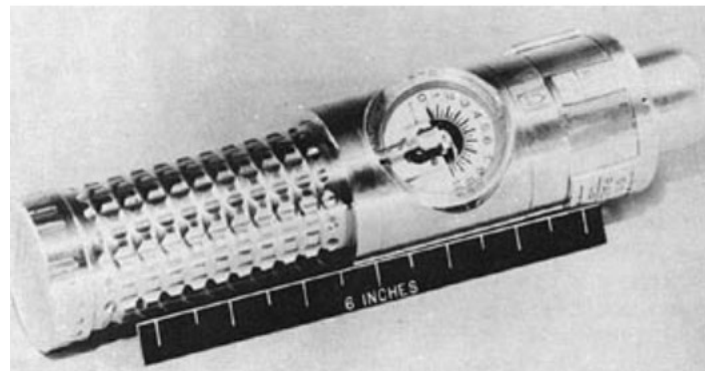
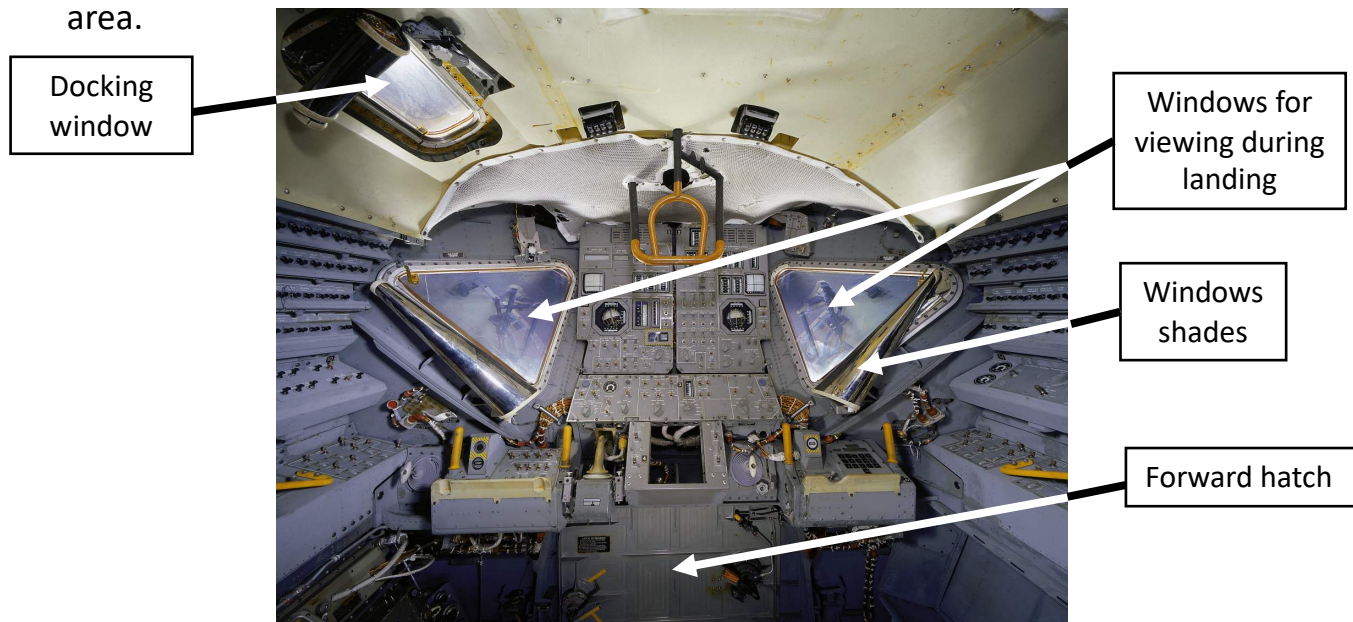


Figure 6. Radiation-survey meter.

Features & Accommodations

- **Hatches:** The LM featured two hatches. The forward hatch was located below the lower display panels (indicated below) and was used as the means of ingress/egress for lunar and inflight EVAs. It was approximately 32"x32" and swung inward. It had to be large enough to fit a crewmember wearing an EVA suit. The overhead hatch allowed crew and equipment to transfer between the LM and the CM while they were docked. It was located in the top of the LM, was roughly 33" in diameter, and also swung inward.
- **Stowage:** Approximately 30% of the total pressurized volume in the LM was dedicated to stowage. Locations of cabinets and shelves are shown in more detail on page 9. Additional storage for EVA equipment was located on the exterior of the descent stage, for use and access during EVAs.
- **Crew Activities:** Given the small habitable volume in the LM, there were no designated areas for any specific crew activity (besides sleep). Eating, suit donning/doffing, sample analysis, and all other tasks were performed in the same area.



The interior of the LM, showing the command console

Design Considerations: Hatches must accommodate the passage of crewmembers and equipment. Stowage areas must be capable of storing all necessary equipment needed for the mission and any samples collected. Habitable volume must support all activities required of the crew.



Apollo Medical Kits

Command Module

- The Apollo CM carried a small medical kit in the spacecraft's lower equipment bay. It contained oral drugs and pills (for pain, motion sickness, and diarrhea; as well as stimulants, antibiotics, decongestants, and aspirin), injectable drugs (for pain and motion sickness), bandages, topical agents (first aid cream, sun cream, and an antibiotic ointment), and eye drops.
- Pills and tablets in the medical kit were packaged so that the crew had easy access to the medication at all times. The pills were sealed individually in strips of 12 or 24 cells. Pressure-related problems in medication packaging were resolved by puncturing each cell with a small pin; the hole made it possible for the air to vent when under reduced-pressure conditions (the medical supplies would have been packaged at standard sea level pressures, but while in space the Apollo CM was pressurized to 5 psi).



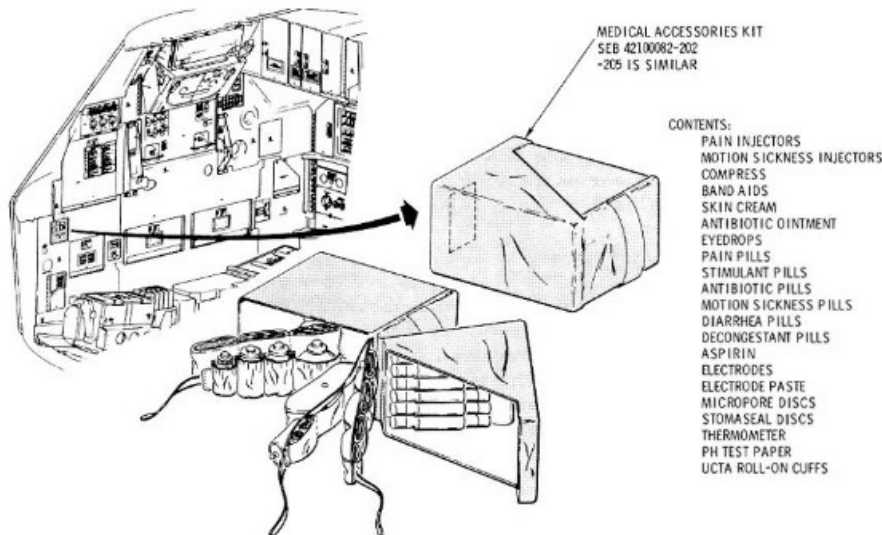
CM medical kit was made of Betacloth and measured approximately 7" x 5" x 5.



Apollo medical kit

Lunar Module

- The LM contained a smaller medical kit.
- The kit was located in the left-hand midsection, readily accessible to both crewmembers.
- Size 19.1 x 14 x 3.8cm (7 1/2 x 5 1/2 x 1 1/2 in.).



Medical Accessories Kit

Lunar Module Medical Kit

Medical Package Assembly	Quantity
Rucksack	1
Stimulant pills (Dexedrine)	4
Pain pills (Darvon)	4
Decongestant pills (Actifed)	8
Diarrhea pills (Lomotil)	12
Aspirin	12
Band-aids	6
Compress bandages	2
Eye Drops (methylcellulose)	1
Antibiotic ointment (Neosporin)	1
Sleeping pills (Seconal)	6
Anesthetic eye drops	1
Nose drops (Afrin)	1
Urine collection and transfer assembly roll-on cuffs	6
Pronestyl	12
Injectable Drug Kit	Quantity
Injectable drug kit rucksack	1
Lidocaine (cardiac)	8
Atropine (cardiac)	4
Demerol (pain)	2

Design Considerations: Kits need to be easily accessible and packaging needs to withstand pressure changes and account for longer duration missions on the Lunar surface.

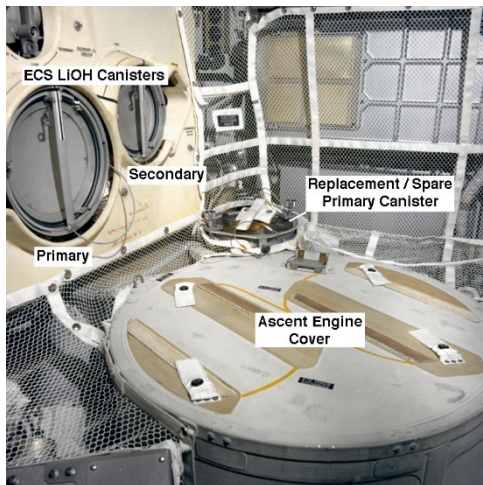
Atmosphere – Carbon Dioxide

Carbon Dioxide Apollo Requirement: Carbon dioxide (CO₂) removal by lithium hydroxide (LiOH) absorption and limited to a partial pressure of 1013 N/m² (7.6 mmHg).

Lunar Module LiOH Circular Canister

- Two used for LM - The primary canister contains a LM cartridge with a capacity of 41 man-hours; the secondary canister, a Personal Life Support System (PLSS) cartridge with a capacity of 14 man-hours
- Approximately 13 pounds each
- Contaminant Control Assembly - This assembly contains an expendable LiOH and charcoal cartridge that filters foreign particles and removes carbon dioxide and odors from the oxygen ventilation loop
- CO₂ partial pressure in atmosphere delivered to astronauts - **6.75 mmHg max**

Location of
LM CO₂
Removal
Canisters



LM CO₂
Removal
Canister

CM LiOH Square Canister

- Two were used at a time, they were alternately changed every 12 hours
- A total of 30 canisters were taken for the typical lunar flight
- Approximately 8 pounds each
- Dimensions: 18.4 x 13.3 x 18.4cm, (7 1/4 x 5 1/4 x 7 1/4 in., 13/16lb.)
- Flight measurements indicated that CO₂ partial pressure seldom rose above 400N/m² (**3 mmHg**)
- For three-man operations, the elements were changed every 24 hours, but the replacement times were staggered every 12 hours to reduce the variation in CO₂ partial pressure levels



CM CO₂ Removal Canister

Design Considerations: The updated NASA-STD-3001 Volume 2 Rev C requirement for one-hour partial pressure CO₂ levels is limited to 3 mmHg. There are also standards to minimize having different size/shapes devices/filters to minimize ease of use (reduce time/training) and redundancy (refer to Apollo 13 mishap).

9



Back-Up



Major Changes Between Revisions

Original → Rev A

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev C.



Referenced Standards

NASA-STD-3001 Volume 1 Revision B

[V1 3000] Medical Management All terrestrial and in-mission medical aspects included in this NASA Technical Standard shall be in accordance with current U.S. medical care standards, with limitations as imposed by mission constraints, and managed by the Flight Medicine team, which includes, but is not limited to, the Flight Medicine Clinic, Crew Surgeon, Deputy Crew Surgeon, and their designees, including the in-mission medical care providers (Crew Medical Officers).

[V1 3003] In-Mission Preventive Health Care All programs shall provide training, in-mission capabilities, and resources to monitor physiological and psychosocial well-being and enable delivery of in-mission preventive health care, based on epidemiological evidence-based probabilistic risk assessment (PRA) that takes into account the needs and limitations of each specific design reference mission (DRM), and parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. The term “in-mission” covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission preventive care includes, but is not limited to: (see NASA-STD-3001, Volume 1 Rev B for full standard).

[V1 3004] In-Mission Medical Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, clinical practice guidelines and expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses should consider the needs and limitations of each specific DRM and vehicles. The term “in-mission” covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, are to include, but are not limited to: (see NASA-STD-3001, Volume 1 Rev B for full standard).

[V1 3005] Medical Training for in-Mission Medical Care Providers The level of training of in-mission medical care providers shall be commensurate with the complexity of anticipated medical, mental health, and behavioral conditions, taking into account such aspects as mission duration, destination, capabilities of the medical system, return-to-Earth capability, mission architecture, crew quantity, vehicle design, and the need for autonomous-from-Earth medical care. The term “in-mission” covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth.

[V1 3006] Crew Medical Officers Quantity The program(s) shall train a minimum of two crewmembers per vehicle/platform as Crew Medical Officers (CMOs).

[V1 3007] Medical Evacuation Medical evacuation to a location with a higher level of medical care shall be available for serious illness/injuries occurring during a space flight mission, which are beyond the medical capabilities available at the crew’s location. This might entail evacuation to planetary or orbiting assets, or back to Earth, depending on the scenario, medical needs, and availability of resources at each location.



Referenced Standards

[V1 3008] In-Mission Evacuation to Definitive Medical Care Facilities Plans shall be available to transport severely ill or injured crewmember(s) to appropriate Medical Care Facilities, including Definitive Medical Care Facilities (DMCF) in the event of a contingency.

[V1 3009] Palliative Comfort Care In medical scenarios where onboard medical resources have been exhausted, a timely return to Earth or another location of higher medical capability is not feasible, and survival of the crewmember has been determined to be impossible, palliative comfort care shall be provided.

[V1 3010] Termination of Care Each human space flight program shall have criteria for termination of care.

[V1 3011] Capability to Handle Deceased Crewmembers Each human space flight program shall provide the capability to handle deceased crewmembers.

[V1 6007] Medical and Survival Kits Vehicle medical kits (routine and survival) shall be provided for all phases of the mission.

NASA-STD-3001 Volume 2 Revision C

[V2 6002] Inert Diluent Gas Cabin atmospheric composition shall contain at least 30% diluent gas (assuming balance oxygen).

[V2 6003] O₂ Partial Pressure Range for Crew Exposure The system shall maintain inspired oxygen partial pressure (P_{iO_2}) in accordance with Table 1, Inspired Oxygen Partial Pressure Exposure Ranges.

[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels The system shall limit the average one-hour CO₂ partial pressure (P_{iCO_2}) in the habitable volume to no more than 3 mmHg.

[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure The system shall maintain the pressure to which the crew is exposed to between 26.2 kPa < pressure ≤ 103 kPa (3.8 psia < pressure ≤ 14.9 psia) for indefinite human exposure without measurable impairments to health or performance.

[V2 6007] Rate of Pressure Change For pressure changes >1.0 psi, the rate of change of total internal vehicle pressure shall not exceed 13.5 psi/min.

[V2 6150] Barotrauma Prevention During a commanded pressure change, the system shall pause within 1 psi of the pause command being issued by the unsuited or suited crewmember, with ability to increase or decrease pressure as needed after the pause.

[V2 6008] Decompression Sickness (DCS) Risk Identification Each program shall define mission unique DCS mitigation strategies to achieve the level of acceptable risk of DCS as defined below within 95% statistical confidence:

- DCS ≤ 15% (includes Type I or isolated cutis marmorata).
- Grade IV venous gas emboli (VGE) ≤ 20%.
- Prevent Type II DCS.

[V2 6009] Decompression Sickness Treatment Capability The system shall provide DCS treatment capability.

[V2 6053] Lunar Dust Contamination The system shall limit the levels of lunar dust particles less than 10 μm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m³ during intermittent daily exposure periods that may persist up to 6 months in duration.



Referenced Standards

[V2 6064] Sustained Translational Acceleration Limits The system shall limit the magnitude, direction, and duration of crew exposure to sustained (>0.5 seconds) translational acceleration by staying below the limits in Figure 4—Gx Sustained Translational Acceleration Limits (Seated), Figure 5—Gy Sustained Translational Acceleration Limits (Seated), and Figure 6—Gz Sustained Translational Acceleration Limits (Seated) for seated posture, and Figure 7—Gx Sustained Translational Acceleration Limits (Standing), Figure 8—Gy Sustained Translational Acceleration Limits (Standing), and Figure 9—Gz Sustained Translational Acceleration Limits (Standing) for standing posture.

[V2 6065] Rotational Velocity The system shall limit crew exposure to rotational velocities in yaw, pitch, and roll by staying below the limits specified in Figure 9—Rotational Velocity Limits.

[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation The system shall prevent the crew exposure to sustained (>0.5 second) rotational accelerations caused by cross-coupled rotations greater than 2 rad/s^2 .

[V2 6067] Transient Rotational Acceleration The system shall limit transient (≤ 0.5 seconds) rotational accelerations in yaw, pitch, or roll to which the crew is exposed and the limit used appropriately scaled for each crewmember size from the 50th percentile male limits of $2,200 \text{ rad/s}^2$ for nominal and $3,800 \text{ rad/s}^2$ for off-nominal cases.

[V2 6069] Acceleration Injury Prevention The system shall mitigate the risk of injury to crewmembers caused by accelerations during dynamic mission phases per Table 5, Acceptable Injury Risk Due to Dynamic Loads.

[V2 6070] Injury Risk Criterion The system shall limit crew exposure to transient translational acceleration (≤ 0.5 seconds) by limiting the injury risk criterion (β/beta) to no greater than 1.0 (Low) for seated or standing crew as defined by Dynamic Response (DR) limits in NASA/TM-20205008198 Table 2 “Updated Dynamic Response Limits for Standing”, while crew are restrained as required in NASA/TM-2013-217380REV1 for seated crew, or NASA/TM – 20205008198 for standing crew.

[V2 6111] Dynamic Mission Phases Monitoring and Analysis The system shall collect vehicle and crewmember acceleration parameters, specific kinematic responses, and associated metadata, during all dynamic mission phases and suited operations (defined as ascent, abort, entry, descent, landing, postlanding, and EVA operations) to correlate with any injuries incurred by crewmembers.

[V2 7016] Personal Hygiene Capability Personal hygiene items shall be provided for each crewmember, along with corresponding system capabilities for oral hygiene, personal grooming, and body cleansing.

[V2 7020] Body Waste Management Capability The system shall provide the capability for collection, containment, and disposal of body waste for both males and females.

[V2 7026] Body Waste Odor The system shall provide odor control for the body waste management system.

[V2 7050] Stowage Provisions The system shall provide for the stowage of hardware and supplies, to include location, restraint, and protection for these items.

[V2 7053] Stowage Interference The system shall provide defined stowage locations that do not interfere with crew operations.

[V2 7064] Trash Accommodation The system shall provide a trash management system to contain, mitigate odors, prevent release, and dispose of all expected trash.



Referenced Standards

[V2 8001] Volume Allocation The system shall provide the defined habitable volume and layout to physically accommodate crew operations and living.

[V2 8005] Functional Arrangement Habitability functions shall be located based on the use of common equipment, interferences, and the sequence and compatibility of operations.

[V2 8006] Interference The system shall separate functional areas whose functions would detrimentally interfere with each other.

[V2 8007] Spatial and Interface Orientation The system shall have consistent spatial and interface orientations relative to a defined vertical orientation.

[V2 8013] Intravehicular Translation Paths The system shall provide intravehicular activity (IVA) translation paths that allow for safe and unencumbered movement of suited and unsuited crew and equipment.

[V2 8027] Hatchway Size and Shape Hatchways and doorways shall be sized and shaped to accommodate all planned translations, including unrestricted passage of a suited crewmember and crewmembers carrying cargo or equipment.

[V2 11005] EVA Translation Path Hazard Avoidance EVA translation paths shall be free from hazards.

[V2 8033] Restraints for Crew Tasks The system shall provide restraints for expected crew operations.

[V2 8038] Restraint and Mobility Aid Standardization Restraints and mobility aids shall be standardized, clearly distinguishable, and located to aid crewmembers in starting or stopping movement, changing direction or speed, or translating equipment.

[V2 8040] Mobility Aid for Assisted Ingress and Egress Mobility aids shall be provided for the assisted ingress and egress of suited or unsuited crewmembers.

[V2 8041] Unassisted Ingress, Egress, and Escape Mobility Aids Mobility aids shall be provided for ingress, egress, and escape of crewmembers without assistance from other crew or ground personnel.

[V2 8042] Mobility Aid Provision Mobility aids shall be provided to support all expected suited and unsuited tasks.

[V2 10030] Display and Control Location and Design Displays and controls shall be designed and located so that they are operable to the required degree of accuracy in expected operating positions and conditions.

[V2 11001] Suited Donning and Doffing The system shall accommodate efficient and effective donning and doffing of spacesuits for both nominal and contingency operations.



Reference List

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